Advanced Magnetics for High Frequency Link Converters

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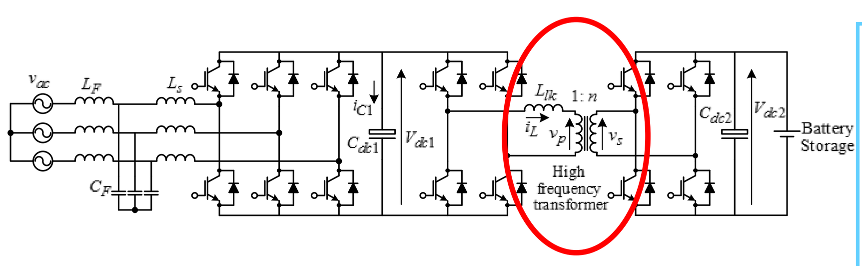
What is the project about?

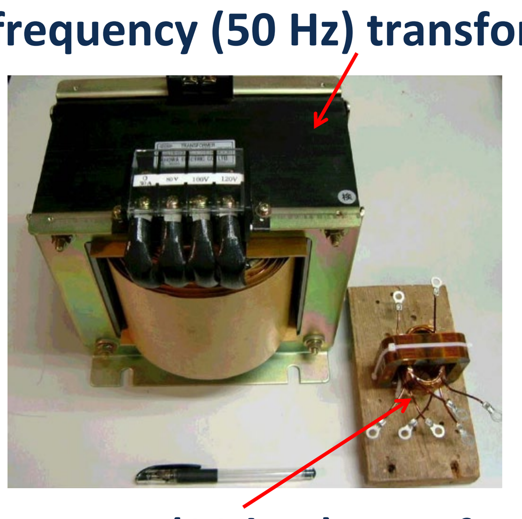
Advanced magnetic materials will enable compact and efficient high frequency DC links and their implementation in transportable energy storage and power conversion systems. Compact and agile systems, able to fit inside a single semi-trailer, will significantly decrease both installation cost and time for solar, wind, and geothermal energy systems in even extremely remote locations. Innovative magnetic core materials suitable for high frequency link converters that can perform without active cooling are being fabricated. Iron nitride (γ'-Fe_4N), manufactured into magnetic components for the first time ever, will lead to lighter, smaller, more affordable, and higher efficiency transformers required for transportable energy storage systems and the widespread adoption of renewable energy.

Why are we doing this? Benefits of a High Frequency Transformer



S. Kulasekaran, R. Ayyanar, Analysis, Design, and Experimental Results of the Semidual-Active-Bridge Converter, IEEE Transactions on Power Electronics, 29 (2014).

Line frequency (50 Hz) transformer



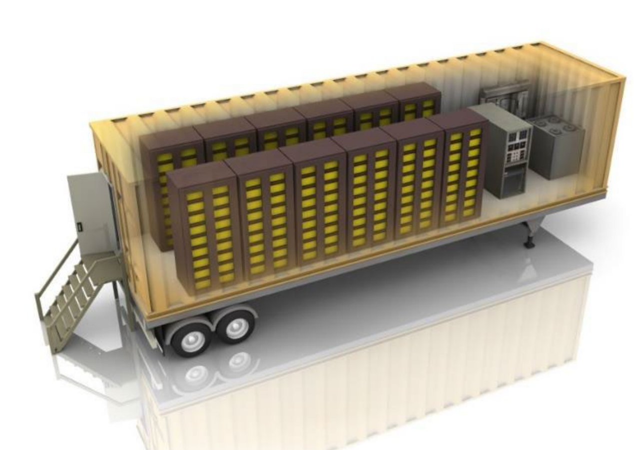
High frequency (20 kHz) transformer

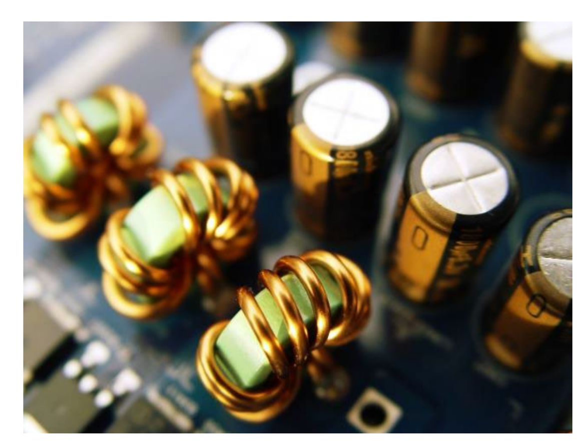
S. Krishnamurthy, Half Bridge AC-AC Electronic Transformer, IEEE, 1414 (2012).

Objectives:
- Integrate output transformer within power conversion electronics
- Leverage high switching speed, voltage, and temperature performance of WBG semiconductors

Benefits:
- Enable solid state transformer (SST) designs
- Bidirectional power flow enabled through use of dual active bridge (DAB) topologies
- High temperature performance (reduced cooling requirements)
- Decreased size and weight of transformer and power conversion system (PCS)
- Improved reliability, resiliency, and flexibility

Why are we doing this? Transportable Energy Storage and Power Conversion Systems (PCS)





Benefits of Energy Storage:
- Maintain power quality and reliability
  - Improve grid stability and resiliency
  - Enhanced flexibility and control (load leveling, power factor control, frequency and voltage regulation)
- Increase deployment of renewable energy

Benefits of Transportable Systems:
- Lower cost and increased flexibility
- Modular design reduces assembly and validation time
- Faster installation at renewable energy generation sites

Previous Work in the Field

Magnetic Material	J_s (T)	ρ (μΩ·m)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Ferroxcube)	0.52	5x10^6	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	> 200	Low

- No existing magnetic material meets all requirements for SSTs
- γ'-Fe_4N can meet all demands of high frequency transformers
- Note: $J = \mu_0 \cdot M$

Methodology

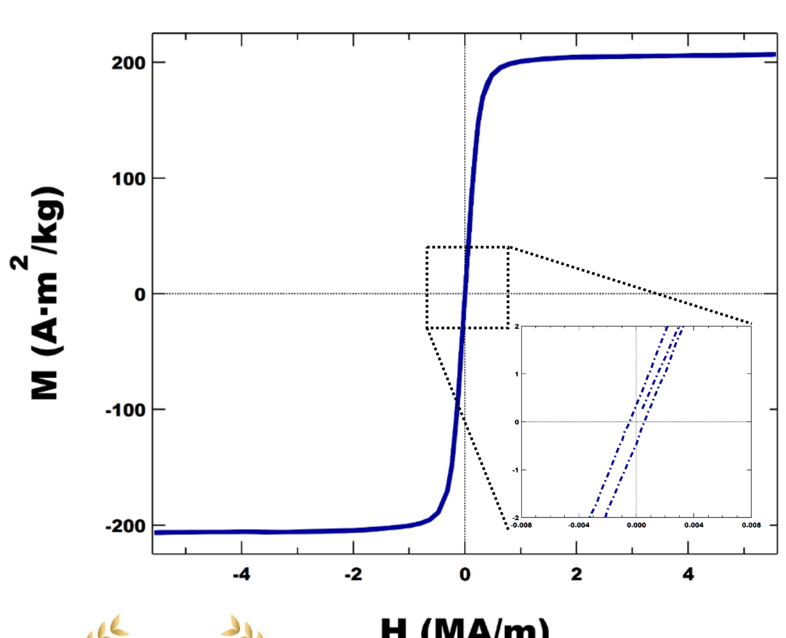
Hypothesis:
- γ'-Fe_4N can meet all requirements of high frequency transformers

Methods:
- Develop pathways for high quality γ'-Fe_4N raw powder synthesis
- Fabricate novel iron nitride and iron nitride based composite magnetic cores
- Test new magnetic cores in relevant environments
- Demonstrate improved performance over state of the art

Innovation/Risk:
- γ'-Fe_4N not fabricated as a bulk material or demonstrated in any device prior to this work

What have we done? Spark Plasma Sintered (SPS) Iron Nitride Cores

First ever bulk γ'-Fe_4N! U.S. Patent #9,963,344



- SPSed at 530°C and 200 MPa
- M_s = 207 Am^2/kg
  - Theoretical M_s = 209 Am^2/kg
- H_c < 500 A/m

Net-shaped, 41 mm O.D., laminated toroid (no machining required)

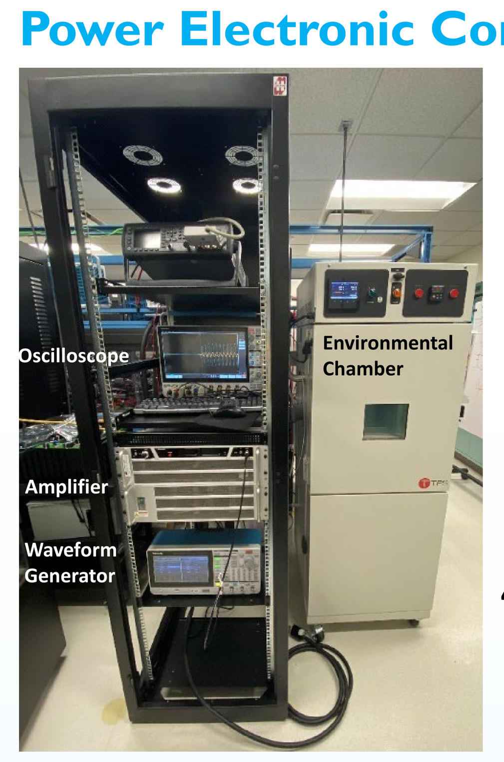
What have we done? Installation of Spark Plasma Sintering (SPS) Equipment

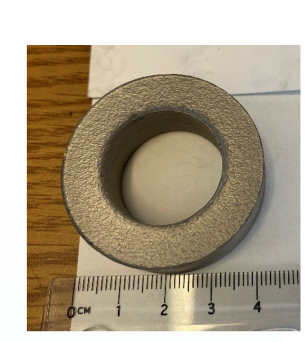
Fuji Dr. Sinter Lab Jr. SPS-632Lx at Sandia National Labs

Initial Fe_4N samples fabricated using Fuji SPS

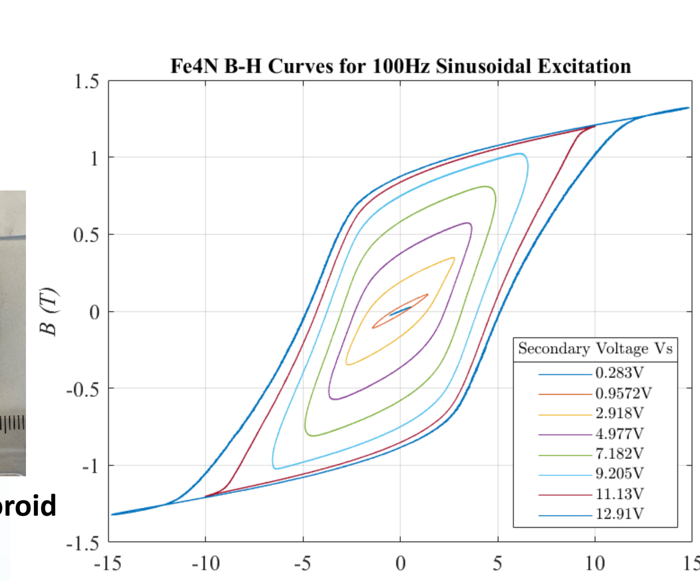
- New capability for Sandia Labs
- Rapid in house prototyping capability for sintered Fe_4N cores
- Max. pressure of 60 kN
- Max. current of 3000 A
- Max. temperature of 2500 °C
- Max. sample diameter of 20 mm
- Max. diameter at 500 MPa = 10 mm

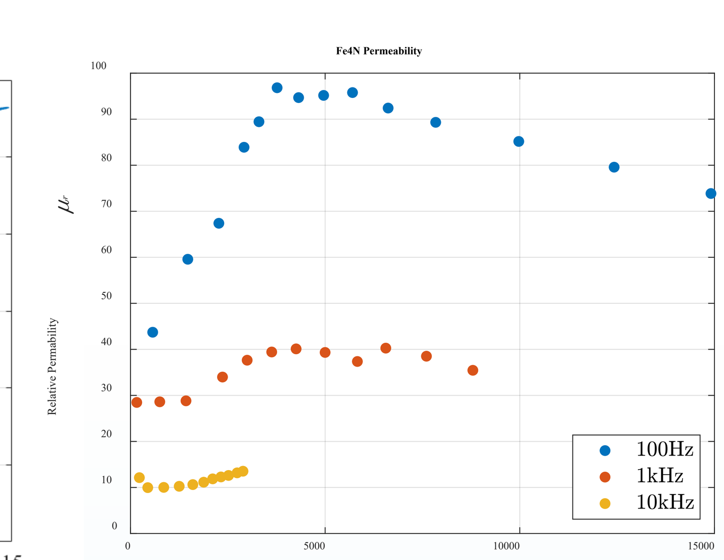
What have we done? Testing of iron nitride > 4 cm cores at the Advanced Power Electronic Conversion Systems (APEX) Lab





41 mm O.D. Fe_4N toroid





Where do we take it from here? Systems level demonstrations & prototypes along with continuous material optimization

FY24 Publications

- M.R. Hoyt, G.I. Falcon, C. J. Pearce, R.E. Delaney, T.E. Stevens, E.M. Johnson, T.M. Szenderski, N.R. Sorenson, S.F. Fultz-Waters, M.A. Rodriguez, L.J. Whalen, T.C. Monson, "Fabrication and characterization of net-shaped iron nitride-amine-epoxy soft magnetic composites," *Frontiers in Materials*, Vol. 10, 2023, pp. 1-14. DOI: 10.3389/fmats.2023.1258382
- J.M. Adamczyk, S.E. Birchall, E.T. Rothermel, S.R. Whetten, E.J. Barrick, C.J. Pearce, R.E. Delaney, J.W. Pegues, D.F. Susan, T.C. Monson, A.B. Kustas, "Characterization of Fe-6Si Soft Magnetic Alloy Produced by Laser-Directed Energy Deposition Additive Manufacturing," Journal of Materials, Vol. 76, 2024, pp. 863–874. DOI: 10.1007/s11837-023-06293-5

Acknowledgements

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